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5.6.3 Modelling Geomorphic systems: Coastal

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ABSTRACT: Models of geomorphic coastal systems incorporate a wide range of ideas: hydraulics, waves, tides, sediment transport and sediment conservation. Models capture these ideas as sets of logical arguments or conceptual models, mathematical formulations, physical scaled models or statistical relationships. None of these models claim to represent reality in all its complexity, but instead provide a formal framework to explore behaviour (i.e. qualitatively and/or quantitatively) of coastal geomorphic systems that are too difficult for us to analyse through reasoning. This chapter outlines the current state-of-the-art in modelling of coastal geomorphic systems and summarises the main strengths and weaknesses of each modelling approach. Rather than favouring one approach over another, the prospect of linking some of the different modelling approaches has been identified as a way forward to develop a system-wide capability for assessing coastal geomorphological change.

KEYWORDS: coast, feedbacks, morphodynamics, nearshore processes, tides, waves

Introduction

Coastal morphology is shaped essentially by the action of wind, waves, currents (i.e. tidal currents, wind and wave induced currents), and tides (i.e. astronomical and meteorological). Coastal regions offer some of the most spectacular, dynamic and risky environments to be found anywhere in the world, with 40% of the world's population living within 100km of the coast (Becker and Payo, 2013).

Our understanding of coastal morphology has made significant progress during the past decades (Dronkers, 2005). The productivity of coastal research has benefited from refined observation techniques and improved models. Field observations contribute to new understanding and knowledge of systems, and thus support, update or challenge coastal models. They are also critical in deriving parameterisations in numerical models as well as in validating these models. Field observations have been extensively covered in chapters 2 and 3 of this book and, therefore, this chapter focuses on coastal geomorphic models.

Geomorphic coastal systems models combine understanding of hydraulics, waves, tides, sediment transport and sediment conservation that are captured as: (1) a set of logical arguments or conceptual model; (2), mathematical formulations; (3) a physical scaled-model; or (4) statistical relationships. This growth in understanding is encouraging but is also highly atomized due to the mainstream reductionist approach in science, making it daunting to newcomers. The aim of this paper is to provide a holistic overview of the current state of the art in modelling coastal geomorphic environments.

For each of the four main types of geomorphic model mentioned above, this chapter presents: (i) an overview of the key concepts and particularities of the coastal environment that influence the modelling approach, and (ii) a brief assessment of the main strengths and weaknesses of applying each modelling approach in research and applied geomorphology enquiries. For the reader seeking further information, key literature is cited throughout the text.

Conceptual models

Overview

A system is a structured set of objects and/or attributes (Chorley and Kennedy, 1971). These objects and attributes consist of components or variables (i.e. phenomena which are free to assume variable magnitudes) that exhibit discernible relationships with one another and operate together as a complex whole, according to some observed pattern.

The very concept of a coastal geomorphic system is a human abstraction or conceptual model. Some researchers have identified boundaries where the flows of matter and energy are distinct from the surrounding environment outside the system (Christopherson, 1997), based on differences in morphological appearance and behaviour (Eleveld, 1999), landform response time (Eliot, et al., 2013) or at zones of sediment transport convergence (and, more rarely, divergence), which indicate zones of reduced transport. The use of the latter to define boundaries can be found in the literature with different terms but similar meaning: coastal sediment cell, coastal tract, coastal cell, littoral cell, coastal compartment, or coastal sector. In particular, the work of Cowell, et al. (2003b) on the coastal tract provides a benchmark for providing a formal framework for aggregation of processes by adding a hierarchy of scales to the coastal cell concept.

Cowell, et al. (2003a) defined the coastal tract in both physical and abstract terms to include the observer into the definition. Under the physical realm, "*the coastal tract is a spatially contiguous set of morphological units representative of a sediment-sharing coastal cell" (Cowell, et al., 2003a, page 815)*. From the observer point of view, "*the tract also is an abstract entity (or meta-morphology) constructed (or templated) for analysis and prediction of a specific site or region in nature, on an associated time-scale*" *(Cowell, et al., 2003a, page 815)*. Alongshore homogeneity is a fundamental assumption when defining the coastal tract that justifies treating along-shelf sediment fluxes as boundary conditions. Within each coastal tract, the hierarchy approach is used to identify pragmatically system constituents at each scale (Figure 1). While the coastal tract is useful to identify scale and order of behaviour, the problem of aggregating sub-scale processes to the scale of interest remains unresolved due to the lack of a formal aggregation theory (Cowell, et al., 2003b, de Vriend, 1991, Werner, 2003). Other limitations of conventional coastal cell approaches are that they are ill-suited for the representation of broad-scale linkages between estuarine, coastal and offshore systems (Cooper and Pontee, 2006) or long-range suspended sediment pathways, which operate at multiple scales (Keen and Slingerland, 1993).

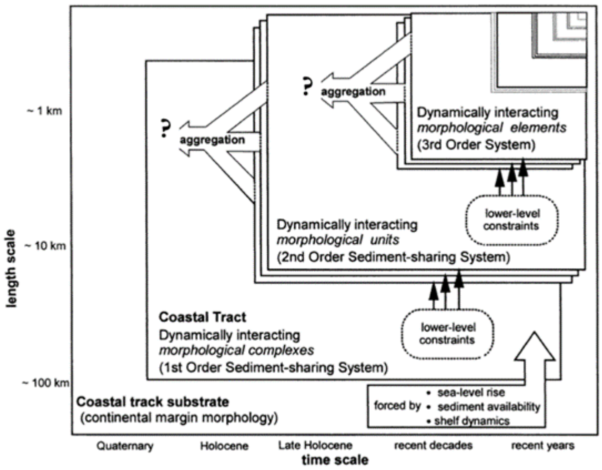

Figure 1: The nested system of the coastal tract cascade highlights the needs of aggregating smaller scale processes into larger scale (adapted from Cowell, et al. (2003a). Reproduced with permission of the Coastal Education and Research Foundation, Inc).

Another set of useful concepts for coastal geomorphology enquiries are those of feedbacks and emergent behaviours. These concepts in geomorphology have been long recognised (Schumm, 1991, Schumm and Lichty, 1965), but it has been in recent decades when views of change, disturbance, response and recovery have expanded considerably (Phillips, 2009). Conceptual frameworks emphasizing single-path, single-outcome trajectories of change have been supplemented – not replaced – by multi-path, multi-outcome perspectives. In this context, Phillips (2009) argues that any attempt to explore change and response should seek to identify potential feedbacks, determine their signs, and assess their relative importance. This is especially important when studying coastal systems in which a broad range of feedback mechanisms drives the system's evolution (i.e. Dronkers, 2005).

A feedback is a change to a component of the system that causes a knock-on effect that further alters the original change. A positive feedback amplifies the initial change. For example, as waves erode a cliff, granular material will be released, which may abrade the shore platform, resulting in even more cliff erosion. Negative feedbacks have the opposite effect of the initial change. For example, as the shore platform is eroding, it becomes wider and gentler diminishing the rate of mass wasting for the same given offshore wave energy flux. Identifying these feedbacks is the first step towards establishing their relevance at the spatial scales of geomorphological models (Lane, 2013). As an ever-greater number of feedbacks are identified and appreciated, the need to map them into a coherent framework is needed. Several methods have been developed to formally describe these linkages. Such methods usually involve some form of diagram or schematic that illustrates the flows of mass or energy (Stock and Flow Diagrams), e.g. Townend (2003), the existence/non-existence of a link (Network Models), i.e. Karunarathna and Reeve (2008), or the positive/negative nature of the feedbacks and their strength (Causal Loop Diagrams), i.e. Payo, et al. (2014). Figure 2 shows an example of how the quasi 2D processes involved in shoreline High Angle Wave Instability (HAWI) defined by Ashton, et al. (2001) can be mapped into a Causal Loop Diagram.

Strengths and weaknesses

System analysis and depiction of feedback structures is the first step of numerical modelling (e.g. Capobianco, et al., 1999), but it is often implicit and hence inaccessible. By explicitly mapping the feedbacks included and neglected within the model, the user is better positioned to assess if relevant feedback loops are included. Ensuring that most relevant feedbacks are included in the model is the key for building confidence on any dynamic model behaviour (Barlas, 1996). Whilst these qualitative approaches provide a system view and can, to some extent, provide an indication of possible states and response to perturbations, they do not provide any temporal or spatial quantification of such changes.

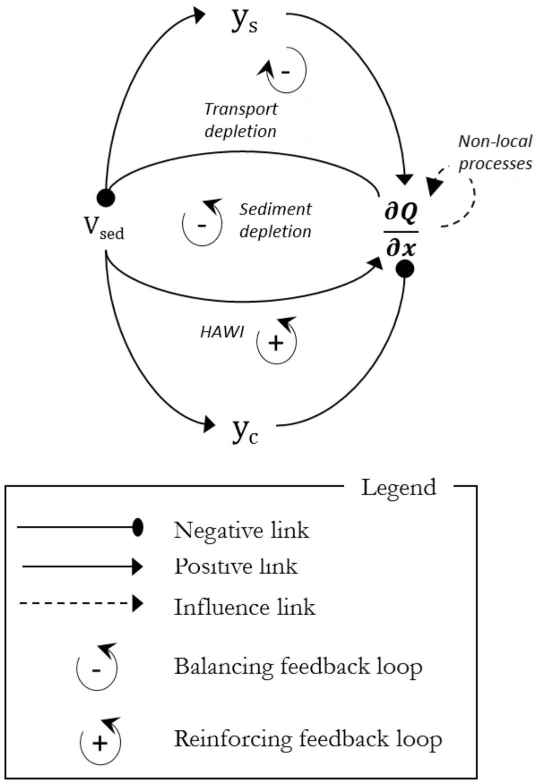

Figure 2: Two negative feedback loops (sediment depletion and transport depletion loops) and one positive feedback loop (HAWI) control the alongshore sediment transport gradient $\frac{\partial Q}{\partial x}$ of sedimentary open coastlines. An increase of the shoreface sediment volume, V_{sed} , induces an increase of the shoreline, y_s, and the depth of closure line,y_c, which leads unambiguously to an increase and decrease of the alongshore sediment transport gradient respectively (from Payo, et al., 2016b).

Numerical modelling

Overview

Traditionally, coastal geomorphic models have been classified based on the main modelled dimension (i.e. Roelvink, 2011) in: coastal profile, coastline and coastal area models. In coastal profile models, the focus is the cross-shore processes and the longshore variability is neglected (Bruun, 1988). In coastline models, cross-shore profiles are assumed to retain their shape even when the coast advances or retreat (Hanson and Kraus, 2011). In coastal area models, variations in both horizontal dimensions are resolved (Amoudry and Souza, 2011). From the system of systems perspective, coastal geomorphic models are better classified as a continuous spectrum from reductionist models to synthesist models (French, et al., 2016). Reductionist models attempt to represent the morphodynamics of the sediment surface by abstracting and averaging transport processes at the finest scale possible while synthesist models (also called behaviour oriented models) attempt to represent the observed behaviour with highly aggregated mathematical expressions.

Coastal area models such as TELEMAC-SISYPHE, Delft-3D and Mike21 are examples of reductionist coastal geomorphic models (for a review see Amoudry and Souza (2011)). In coastal area models, lower order scale models impose the boundary conditions to upper order scales through energy, sediment and water fluxes, while higher order models force morphology changes through bed-morphology update. Landform behaviour emerges from the initial conditions, forcing and internal dynamic interacting at a finite space/time levels. No equilibrium behaviour is assumed but morphology emerges from the processes interactions. The approach updates the bed according to the result of fluid (water/air) forces (time-varying in quasi 3D or 2D) interacting with the sediment load and the bed at different nested domains. To reduce the computational time required to calculate the hydrodynamic attributes every time step, less frequent and smart procedures have been developed such as the Morphological Acceleration Factor (Ranasinghe, et al., 2011). An unstructured, or structured grid (or a hierarchy of nested grids of different sizes), are adjusted to the problem being modelled.

Examples of behavioural modelling include coastline models such as the “Generalized Model for Simulating Shoreline Change” (GENESIS) for diffusion dominated coastal environments (Hanson, et al., 2011), the Coastal Vector Evolution Model (COVE) for coastal environments where morphodynamics is a trade-off of diffusion and instability processes (Hurst, et al., 2015) and the “Soft Cliff and Platform Erosion Model” (SCAPE) model for costal erosive environments (Walkden and Hall, 2011). For example, Hurst, et al. (2015) used the COVE model to examine the behaviour of crenulated-shaped bays forced by differing directional wave climates (Figure 3).

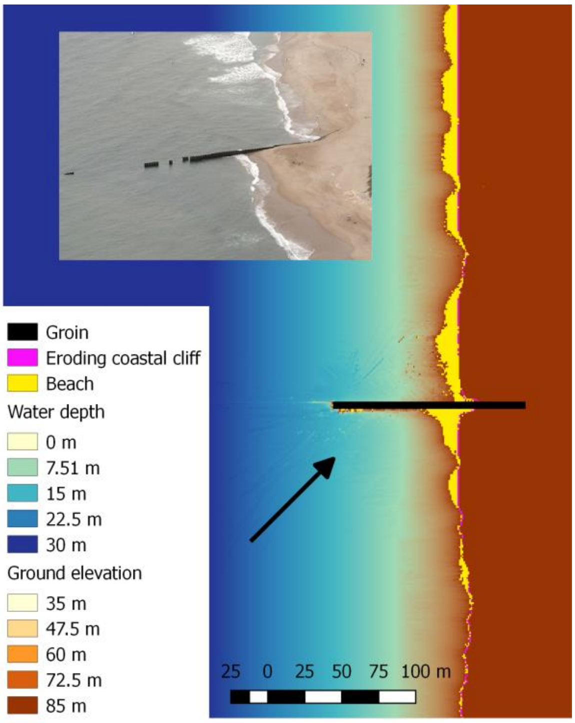

Figure 3: Simulation results showing how a groin interrupt the alongshore sediment transport. Simulation starts with a rectilinear and gently sloping DEM interrupted by a groin and waves coming at 225° (arrow). After one year of simulation an eroding cliff and a beach of different widths is created. Sediment is accumulated at the up-drift side of the groin and eroded on the down drift side where the shadow zone intercepts the coastline.

The key advantages of behavioural models over more reductionist morphodynamic models for large-scale, long-term simulations are stability and robustness (de Vriend, et al., 1993b). In this context, the crudeness and simplicity of the longshore and cross-shore transport modules in coastline models have contributed to the model’s success as they have enhanced its stability. Behavioural models have a limited ability to represent the local effects of coastal structures on the beach, and are more suited to open beach evolution at time scales of about 100 km and 100 years. The main challenge in modelling coastal geomorphic systems is how to deal with complexity that arises due to non-linear behaviour and the way that this complicates scaling of our predictive ability along the time axis (Figure 4).

The scope to reduce the complexity of the morphodynamic problem in coastal geomorphology is more limited than, for example, in fluvial geomorphology. Most fundamentally, the dependence of sediment transport on geophysical flows cannot be quite so readily parameterised as a simple function of topography. Tidal flows, for example, arise from pressure rather than topographic gradients and drive sediment movements that emerge as tiny residuals of opposing gross fluxes. The residual water and sediment movements are much less amenable to robust parameterisation, which favours the retention of more hydrodynamic complexity in models that aim to resolve morphological change. This particularly applies to estuaries and to systems dominated by cohesive sediments. The sediment transport pathways that drive morphological change are highly grain-size dependent (e.g. Bass, et al., 2007) and the interaction between cohesive and non-cohesive sediment pathways can be quite complex, even involving opposing residual fluxes in some tidal inlets (e.g. van de Kreeke and Hibma, 2005).

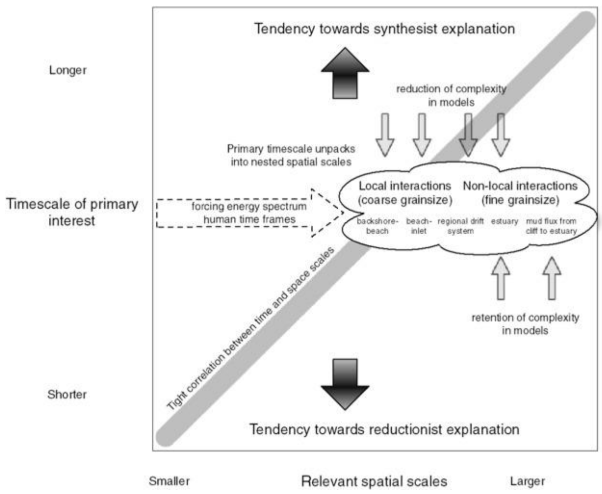

Figure 4: Schematic representation of linkages between a timescale of primary interest (determined with reference to intrinsic forcing periodicities as well as engineering, social and political timeframes) and the associated multiple spatial scales of interaction in coupled coast–estuary–shelf systems (the latter being strongly associated with distinct sediment size fractions). From a modelling perspective, broadly synthesist and reductionist approaches can be brought to bear on various aspects of this coupled system (from French et al. 2016).

There is also the question of how comprehensively to model coupled systems that are complex in their own right and exhibit different scales of behaviour and strengths of horizontal coupling. Change on open coasts is typically mediated by beach grade material (sands, gravels) and littoral drift systems that tend to have a strong serial dependency. Even with a dependence on more distant sources, the filtering effect (e.g. via slower shelf transport rates) acts to decouple sources from their ultimate sinks, such that the problem reduces to one of shorter-range transfers with serial dependency (i.e. dominant direction of littoral drift system). Some estuarine systems also participate in short-range coupling with adjacent coast via tidal deltas and inlet bypassing processes (e.g. Burningham and French, 2006) and the evolution of estuary morphology can exert a considerable influence on the open coast (FitzGerald, et al., 2006). Fusion of reductionist and synthesist approaches may offer the best basis for prediction (e.g. de Vriend, et al., 1993a, van Maanen, et al., 2016)

One possible way forward is the development of model interfaces; software wrappers that allow coupling of models that have been developed independently (Moore and Hughes, 2016, Sutherland, et al., 2014). Significant effort has been made in this direction during the last decade, in particular by the Open Modelling Interface (OpenMI) and Community Surface Dynamics Modelling System (CSDMS). OpenMI is a standard which has emerged from the water sector as a way to link existing stand-alone models that were not originally designed to work together (Gregersen, et al., 2005), while CSDMS draws on a large pool of open-access well understood models (Peckham, et al., 2013).

The promise of OpenMI and CSDMS is to provide a unified system in which various models can be linked to explore broader system behaviour. However, a range of challenges exist when linking component models in this way, including non-trivial technical issues concerning variable names and units (Peckham, et al., 2013), and difficulties associated with fully accounting for the cumulative effect of various assumptions and uncertainties in the constituent models. Furthermore, software-coupling frameworks are themselves agnostic with regard to the spatial structures of component models. This creates a significant challenge, due to notable inconsistencies in the conceptualisations of geometries, volumes and locations of sediment between existing coastal numerical models, in special for large scale coastal behavioural models (Terwindt and Battjes, 1990). For example, the Soft Cliff and Platform Evolution (SCAPE - Walkden and Hall (2011) model assumes a beach of finite thickness perched at the top of the bedrock shore profile, while one-line approaches assume infinite beach thickness. Integrated modelling of complex coastal behavioural systems should, ideally, enable and encourage consistent treatment of the entities that are being modelled. Thus, integrated modelling must go beyond the software coupling issues that have been the focus of OpenMI and CSDMS and deal more directly with the semantics of the various entities being modelled.

An alternative way to address this is by a modular, object-oriented framework in which these entities are the primary constructs (Raper and Livingstone, 1995). In other words, the objects that interact within the framework should correspond to the main constructs considered -- individually, so far -- by modellers of coastal behaviour. An implemented example of this object-oriented approach is the Coastal Modelling Environment (CoastalME) (Payo, et al., 2016a). In CoastalME, change in coastal morphology is formulated by means of dynamically linked raster and geometrical objects. A grid of raster cells provides the data structure for representing quasi-3D spatial heterogeneity and sediment conservation. Other geometrical objects (lines, areas and volumes) that are consistent with, and derived from, the raster structure represent a library of coastal elements (e.g. shoreline, beach profiles and estuary volumes) as required by different landform-specific models. Figure 5, illustrates a proof-of-concept run of CoastalME.

Strengths and weaknesses

Numerical models are non-invasive and often faster and cheaper to run than equivalent physical models. They can also be used to quantify uncertainty and has proven to have good skills simulating the fast geomorphic change associate to storm-events. The main weakness is the limited skills modelling the slow geomorphic change associate to recovery under non-storm conditions (i.e. Kobayashi and Jung, 2012).

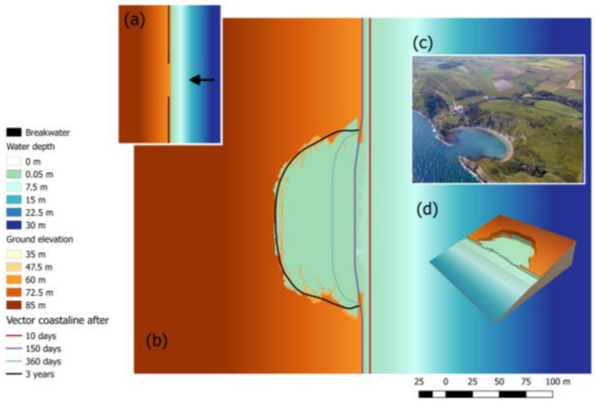

Figure 5: Simulated cove creation on an initially rectilinear coastline. (a) At the start of the simulation, the coastline of a gently sloping topography is protected by a breakwater but a short segment in the centre that is un-protected. (b) Location of the vector coastline at different time steps and final topography after three years of simulation. (c) The resulting cove is bounded by a cliff similar to the Lulworth Cove bay in the south of the UK.

Physical modelling

Overview

A physical coastal model is a scaled representation of a real prototype and is used to find or confirm solutions for engineering problems and to study processes under controlled conditions. Scaling issues of physical models have been discussed in detail in section 5.3 of this book (Green, 2014), therefore only specific aspects of coastal physical models are discussed in this section.

The relevant forces for most coastal hydrodynamics problems are the gravitational forces, friction, and surface tension (Dalrymple, 1985). Thus, the dimensionless products are combinations of the Froude, Reynolds, and Weber numbers. Neglected are compressibility and elasticity effects. Yet the use of the same fluid on both model and prototype prohibits simultaneously satisfying the Froude, Reynolds and Weber number scaling criteria and thus, most coastal models are run respecting Froude's similarity only, which implies that gravitational effects are the most significant and that the viscosity and surface tension of water do not play significant roles.

For coastal sediment models, another set of scale relationships governing the initiation of motion, the transport mode, and the transport rate must be introduced into the model, again with inevitable scale effects. The coastal mobile bed sediment transport and morphology model (Figure 6) is perhaps the most difficult of all physical hydraulic models (Kamphuis, 1985); yet despite the shortcomings it is, in many cases, the most important available instrument to bring about improvements with respect to sediment transport, and erosion. A comprehensive set of guidelines for physical models of mobile sediment can be found in Sutherland and Soulsby (2010).

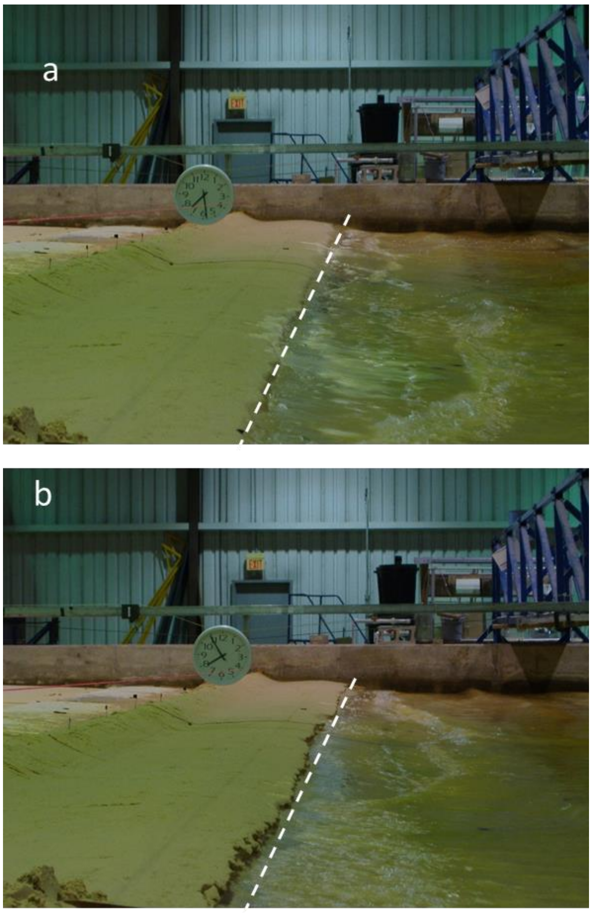

Figure 6: Scarping simulation in a multidirectional wave basin. (a) beach shape at the beginning of the experiment and (b) scarped berm after 143 minutes of wave action (from Payo, et al., 2008).

The Hydralab+ website (www.hydralab.eu) provides an overview of the experimental facilities and instruments in Europe, their sizes and characteristics. The range of model facilities include;

- Current flumes
- Wave flumes
- Wave basins (with and without currents)
- River Physical models
- Tidal physical models
- Oscillating water tunnels and U-tubes
- Oscillating trays, including in current flumes
- Total Environment Simulator
- Rotating facilities, e.g. race track flumes, annular cells, Coriolis facilities

Strengths and weaknesses

Physical models and laboratory experiments remain part and parcel of the research methodology mostly because they allow modelling (especially in facilities that model processes at full scale) of processes that cannot be modelled numerically. Differences between the model and prototype behaviour and results may be due to scale (similarity laws considered and incomplete reproduction of the forces involved), laboratory (model geometry – 2D or 3D influences, reflections; flow or wave generation techniques – turbulence intensity levels, linear wave theory approach; fluid properties, etc.) or measurement (different equipment's used in model and prototype – intrusive or not, probe sizes) effects. The estimation of these effects (qualitatively and quantitatively) affects the results and to know if they can be neglected is a challenge for physical modellers (Heller, 2011).

Statistical modelling

Overview

Statistical models use measurements of past conditions at a site, together with sophisticated statistical techniques, to find evidence of trends, cycles or other smoothly varying modes of change that might be then extrapolated into the future to form a forecast.

Most coastal statistical models are based on the covariance structure of analysed signals (i.e. Reeve, et al., 2016). The underlying assumption of these models is that all information about statistical properties of those signals is contained by that structure. This is equivalent to the assumption that all random variables of the signal are normal (Gaussian). However approximate this assumption may be, it is usually exact enough to be accepted. The most important consequence of normality is that if random variables, centred about their mean values, are orthogonal, then they are uncorrelated and, by virtue of their normality, independent. Methods that fall into this category include Empirical Orthogonal Functions (EOF), Complex Principal Component Analysis (cPCA), Canonical Correlation Analysis (CCA), Singular Spectrum Analysis (SSA) and Multi-channel singular spectrum analysis (MSA).

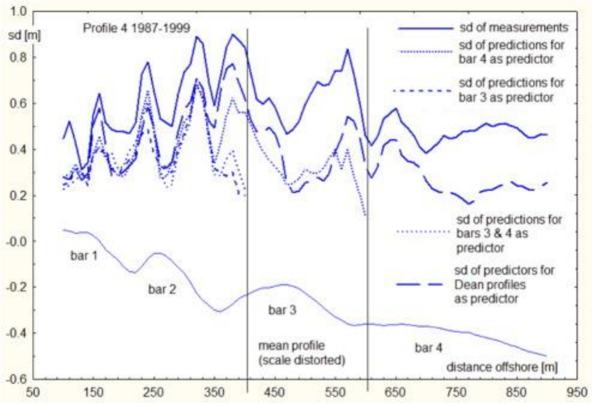

Figure 7: CCA analysis of outer and inner bar interactions at Lubiatowo, Poland (Różyński 2003).

These methods are often used in combination. For example, Różyński (2003) investigated the behaviour of four oscillating bars with empirical orthogonal functions (EOF) to determine the characteristic evolution patterns of multiple longshore bars and with canonical correlation analysis (CCA) to evaluate the importance of interactions among them (Figure 7). If observed patterns are non-stationary nor oscillating, the underlying assumptions of the EOF analysis are violated and the CPCA analysis is more fit for propose (i.e. Ruessink, et al., 2000). The SSA technique can be used to assist in separating noise from underlying irregular but smooth changes in a signal. In one of the first applications of the SSA method to coastal morphodynamics, Różyński, et al. (2001) analysed 16 years of shoreline position measurements along a 2.8 km shoreline segment at Lubiatowo, Poland. No systematic behaviour could be deduced from the observations, but the SSA results suggested that the shoreline exhibits standing wave behaviour with periods lasting several decades found in the western part of the coastal segment, approximately 16 years in the middle part of the segment, and ~ 8 years in the central-eastern part of the segment. A more sophisticated version of the SSA, multi-channel SSA (MSSA), in which covariances in both time and space are computed, was subsequently applied to the same dataset by Różyński (2005).

An example of a statistical model used in predictive mode is the work of de Alegría-Arzaburu, et al. (2010), which described an application of CCA to derive forcing–response relations between the wave climate and shoreline position on a macrotidal gravel barrier located in the southwest of the U.K. Other examples of the use of statistical models in predictive mode among others are Karunarathna, et al. (2015), Horrillo-Caraballo and Reeve (2008), Davidson, et al. (2013) and Kuriyama and Banno (2013).

Strengths and weaknesses

Statistical models can play an important role by providing forecasts that are site specific but independent of any numerical modelling package. When used for prediction, by extrapolating such patterns, statistical models are unlikely to be able to predict changes in coastal system state or configuration unless such changes are captured in the measurement record used for the pattern analysis. A more fundamental weakness of statistical models is the predictability approach to identify causality being ill-suited for the dynamic of coastal system. The predictability approach to identify causality is useful for detecting interactions between strongly coupled (synchronized) variables in non-linear systems (e.g. purely stochastic and linear systems) but, it is problematic in dynamic systems with weak to moderate coupling. This is because the key requirement of separability (i.e. information about a causative factor is independently unique to that variable) is not satisfied in such systems (Sugihara, et al., 2012). While it is accepted that sediment transport, hydrodynamic and bottom change are strongly coupled at scales from hours to years, it seems that it is weak to moderate coupled at decadal and longer time scales (e.g. Houser, 2009).

Conclusions

All types of geomorphic modelling approaches (conceptual, physical, numerical, and statistical) are crucial tools in coastal geomorphic enquiry, and have allowed exploration of a range of system dynamics at a range of spatial and temporal scales. Each model approach has its own strengths and weaknesses. In recent years, the prospect of linking some of the different modelling approaches has been identified as a way forward to develop a system-wide capability for forecasting coastal change.

Understanding the impacts of contemporary climate change (i.e. time scales span decades to centuries) requires a major effort to systematically identify primary geomorphological feedbacks, their signs and their strength. Thus, we establish a line of thought upon which we can base our model concept and our process research and model development policy. The realization of this policy will require a co-ordinated effort of a variety of disciplines and institutes, and the deployment of all scientific potential available.

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